Unraveling the Plasma Physics of Galactic Jet Formation via Laboratory Experiments

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Outline:

- Galactic jet introduction
- Experimental basis for simulating jet formation
- Recent experimental results
- Proposed new experiments

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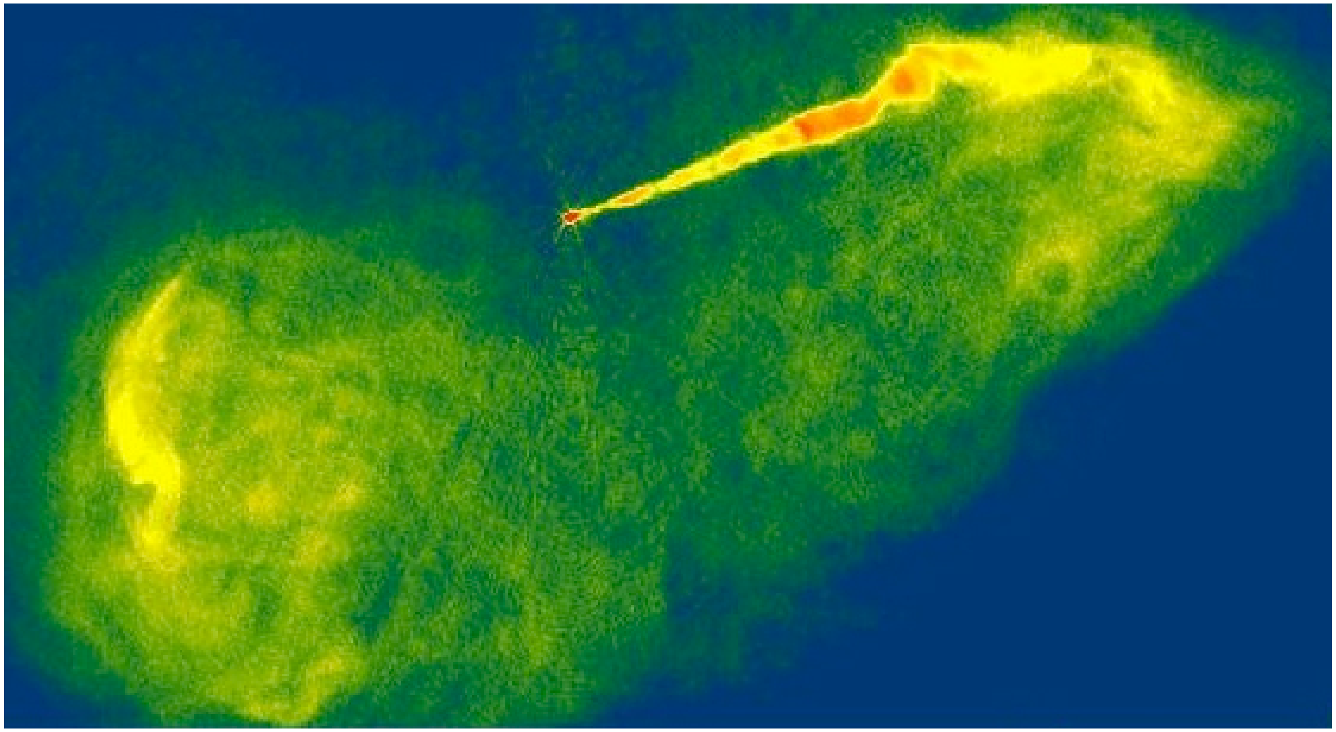
Galactic Jets Have Cosmological Impact



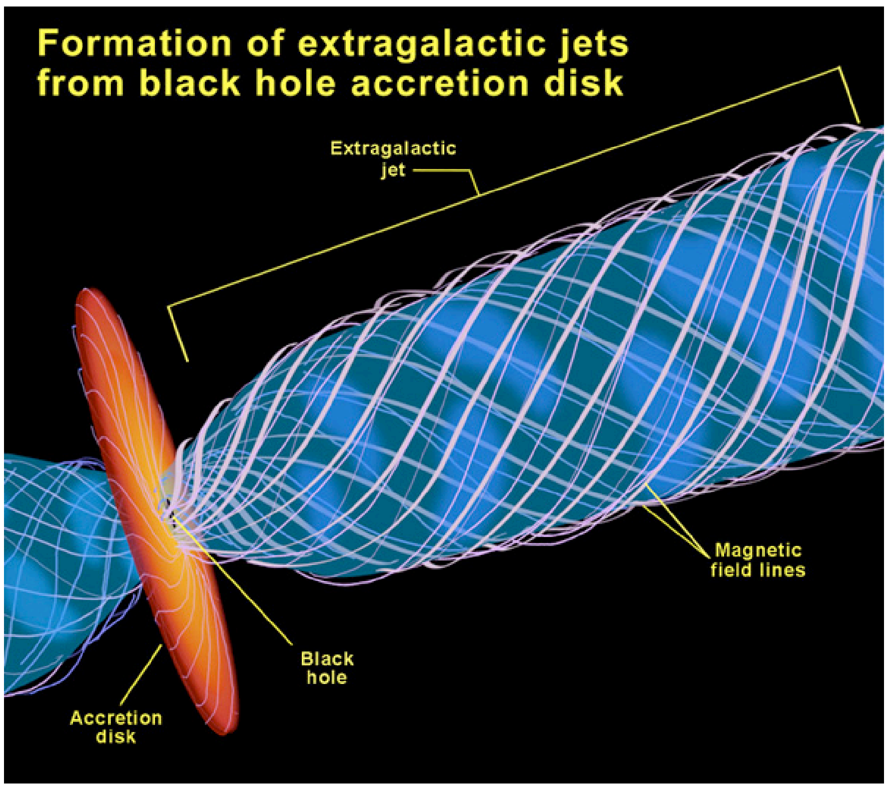
~10% of gravitational energy released from SMBH formation →

magnetic energy transported by jet to extra-galactic scales

Kronberg et al.; Colgate et al.

Galactic Jet Formation Requires Plasma Physics Description

Magnetic field twisted by ionized rotating accretion disk



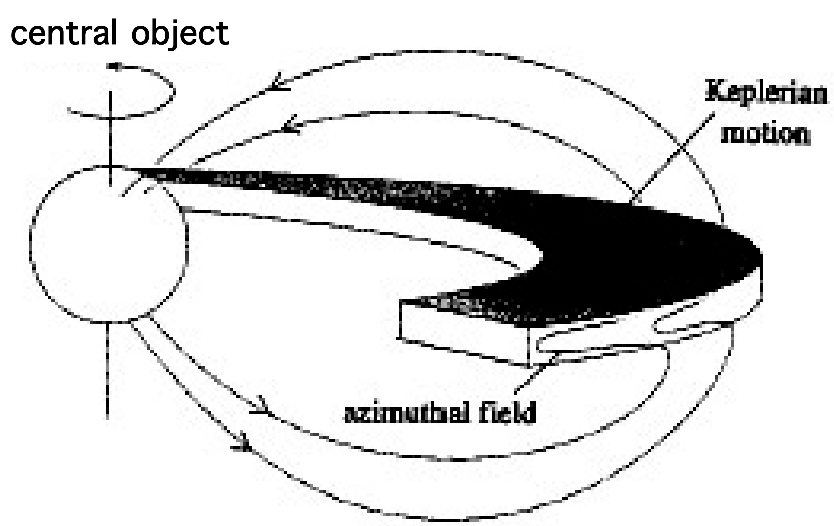
MHD models

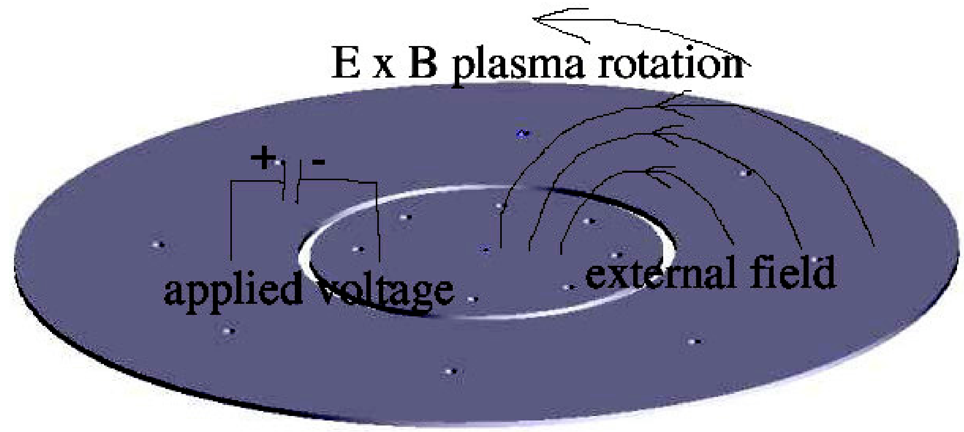
(Lovelace, Blandford, Lynden-Bell & disciples)

Nonlinear plasma physics:

- Collimation dependence on disk rotation
- Instability onset/saturation
- Flux conversion dynamo
- Energy/momentum transfer between jet and background

Plasma Physics of Disk-Jet System Simulated Using Coaxial Electrodes





Disk coronal plasma obeys ideal MHD Ohm's law:

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = 0 \;\rightarrow\; E_R = -V_\theta B_Z + V_Z B_\theta$$

applied voltage (lab) → E_R

Keplerian rotation (disk) → $-V_\theta B_Z$

Field-aligned current twists up background magnetic field and injects magnetic helicity $K = \int \mathbf{A}\cdot\mathbf{B}\, d^3\mathbf{x}$ [flux^2]

Astrophysically Relevant Plasma Conditions Accessible in Laboratory Experiments

- Large magnetic Reynold's number $\rightarrow$ MHD regime (Alfven dynamics much faster than resistive diffusion)

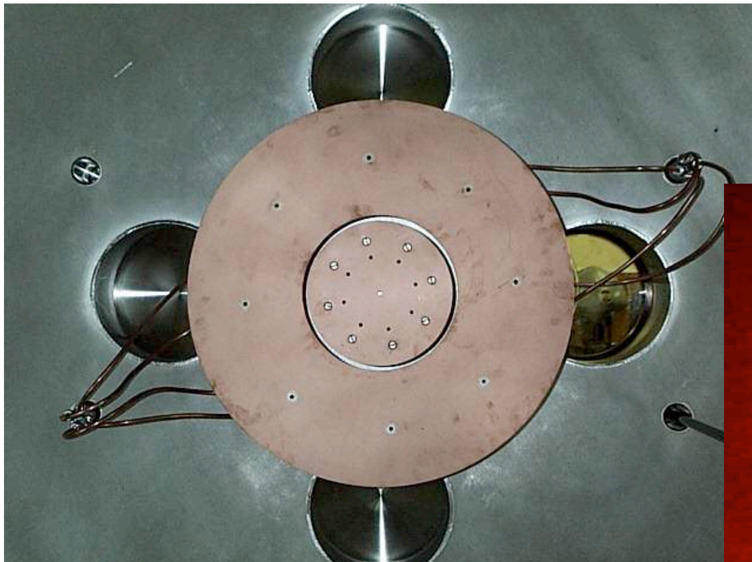
- Very low β plasma (characteristic of disk coronae; plasma tries to "relax" toward force-free state)

- Magnetic helicity injection rate (rotation) scalable from sub to super-Alfvenic

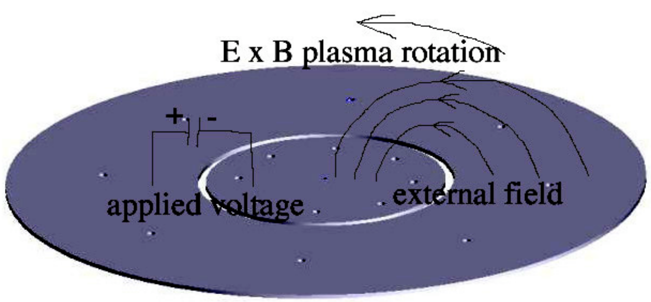
Recent Experiments

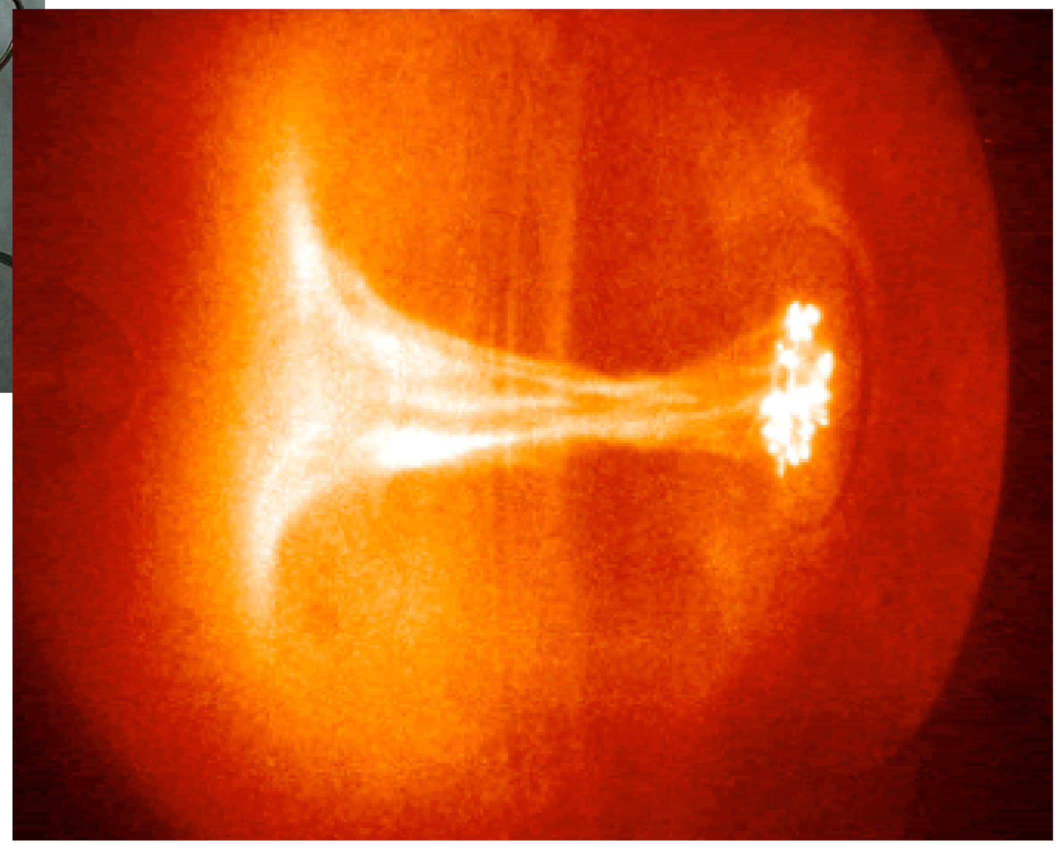
(in collaboration with P. Bellan, Caltech)

Jet Formation By Helicity Injection Demonstrated in Recent Experiments



coaxial electrodes

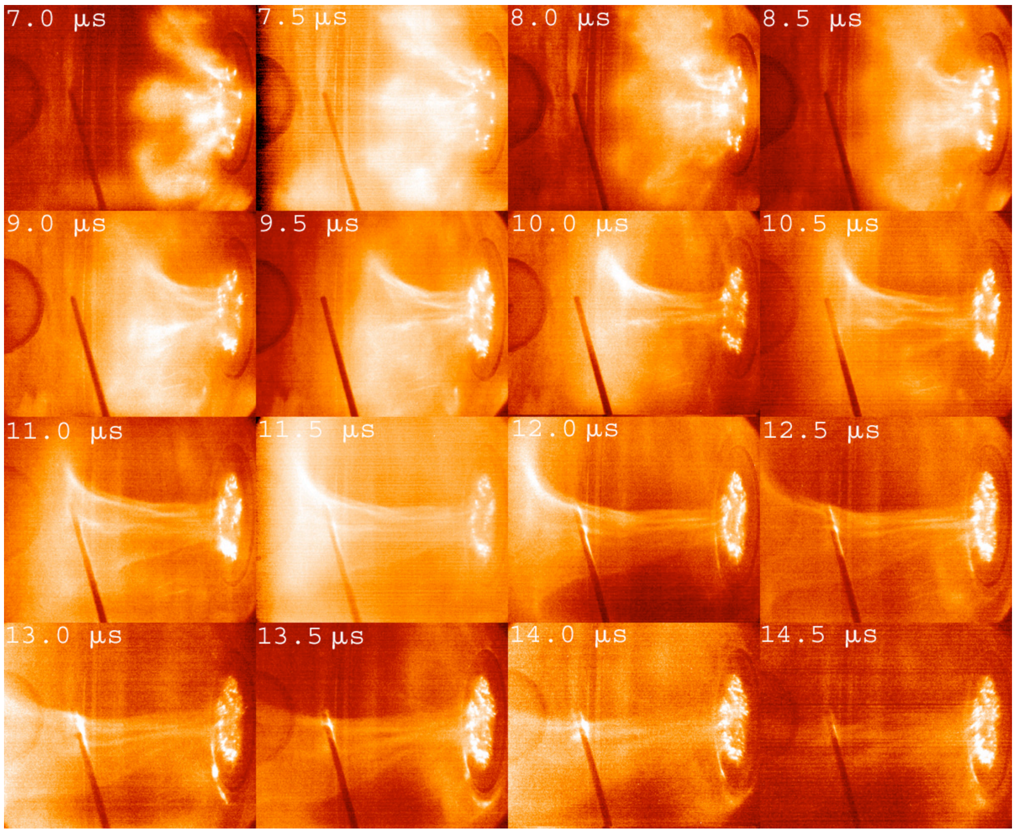


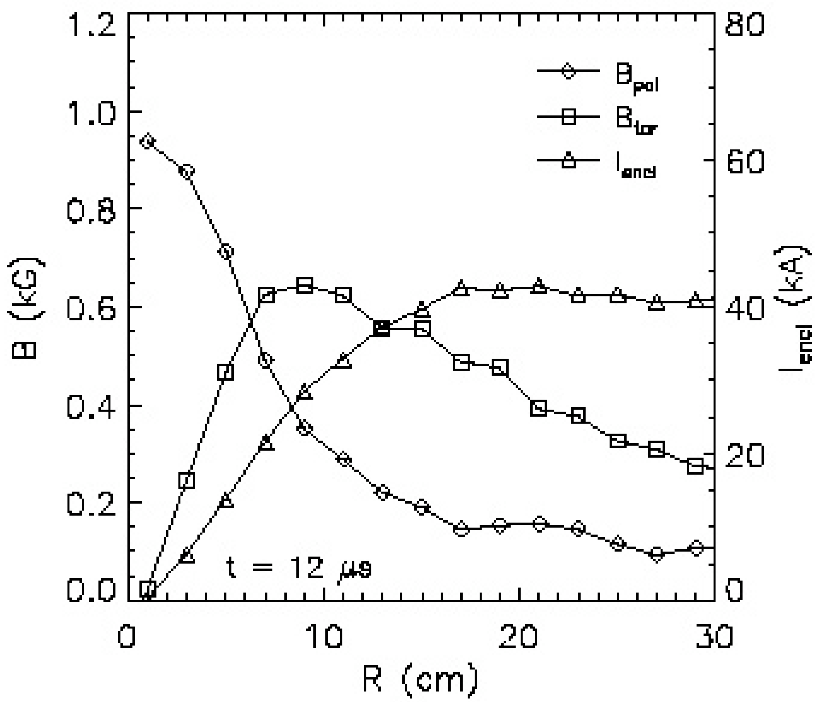


magnetic collimation (movie)

Hsu and Bellan, *MNRAS* **334**, 257 (2002)

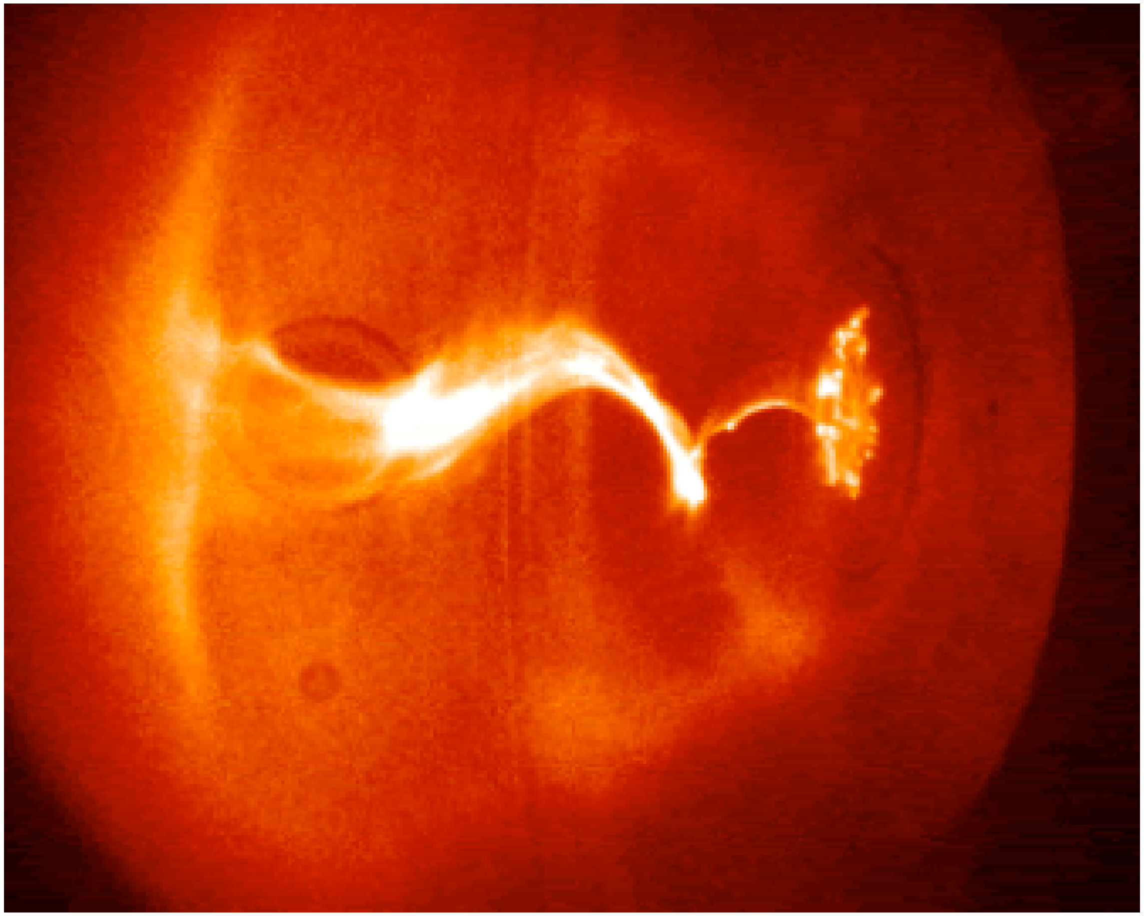
Plasma Column Has Helical Magnetic Field (Screw Pinch)





Hsu and Bellan, *Phys. Plasmas* **12**, 032103 (2005)

Jet Becomes Kinked When MHD Instability Threshold Satisfied



"Kruskal-Shafranov limit"

instability occurs when

$2\pi R B_Z / L B_\theta < 1$

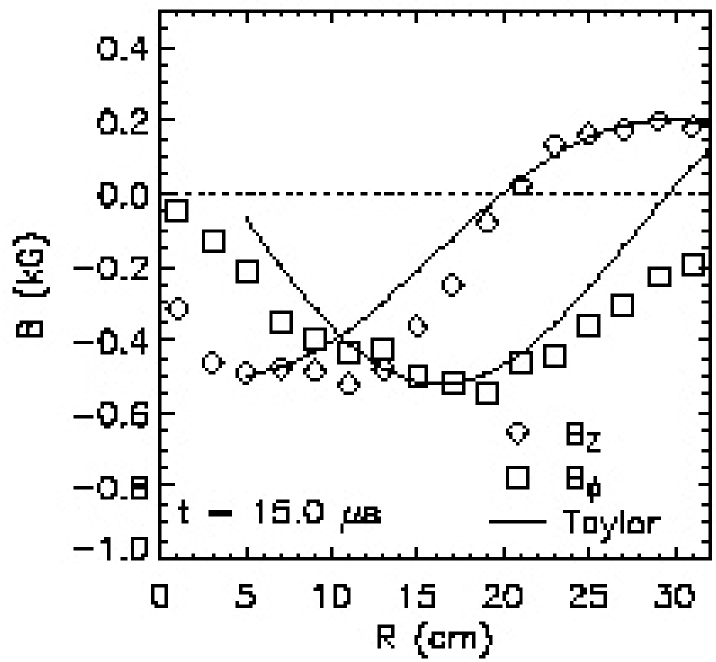
Kink instability (movie)

Hsu and Bellan, *MNRAS* **334**, 257 (2002)
Hsu and Bellan, *PRL* **90**, 215002 (2003)

Kink Provides Flux Conversion "Dynamo" Leading to Relaxed "Spheromak"

- Kink converts toroidal to poloidal flux
- Measured *B*-profiles approach relaxed spheromak state

$$B_Z \sim J_0(\lambda R)$$
$$B_\phi \sim J_1(\lambda R)$$



Hsu and Bellan, *PRL* **90**, 215002 (2003)

Are radio lobes giant spheromaks?

Proposed New Experiments

(in collaboration with X. Tang, T-15)

Proposed Experiments Will Have Several Key New Capabilities

- Helicity injection independent of plasma formation $\rightarrow$ allows very low β to be maintained

- 3rd concentric electrode $\rightarrow$ more control over E_R profile to give Keplerian rotation profile

- Volumetric space and time-resolved measurements of *B*, *n*, *T*, *V*

- Long enough time duration to allow >20 rotations (can collimation survive curse of spheromak?)

Key Dimensionless Parameters Identified

- Helicity injection rate ↔ $E \times B$ rotation

$$V_{\mathrm{m}} = \mathrm{V}_{E\times B}/\mathrm{V}_{\mathrm{A}}$$

$$\sim (E/B)/(B/\rho^{1/2}) \sim \rho^{1/2}\, V_{\mathrm{applied}}/B^2$$

Scan V_{m} from 0.1 (sub-Alfvenic) to 10 (super-Alfvenic)

- Instability threshold

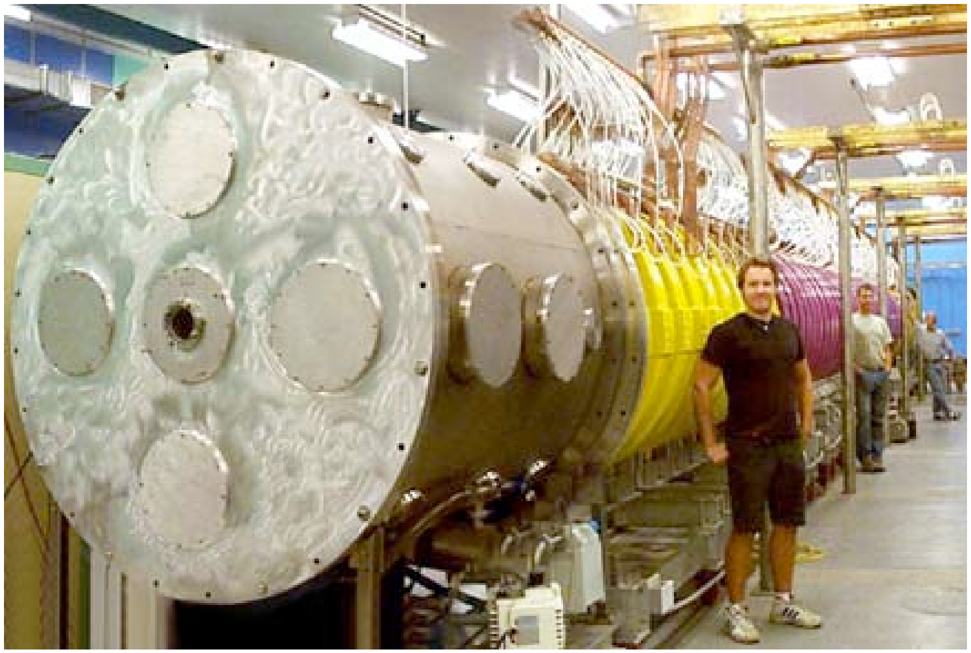
$$V_{\mathrm{s}} = V_{\mathrm{applied}}/\langle V_{\mathrm{drop}}\rangle$$

$$\text{where } \langle V_{\mathrm{drop}}\rangle \sim \eta B/\mu_0$$

Scan V_{s} from 0.1 (stable) to 10 (unstable)

X. Tang et al., BAPS (2002, 2003) and Phys. Plasmas (2004).

New Experiments Will Be Done on State-of-the-Art Plasma User Facility at UCLA



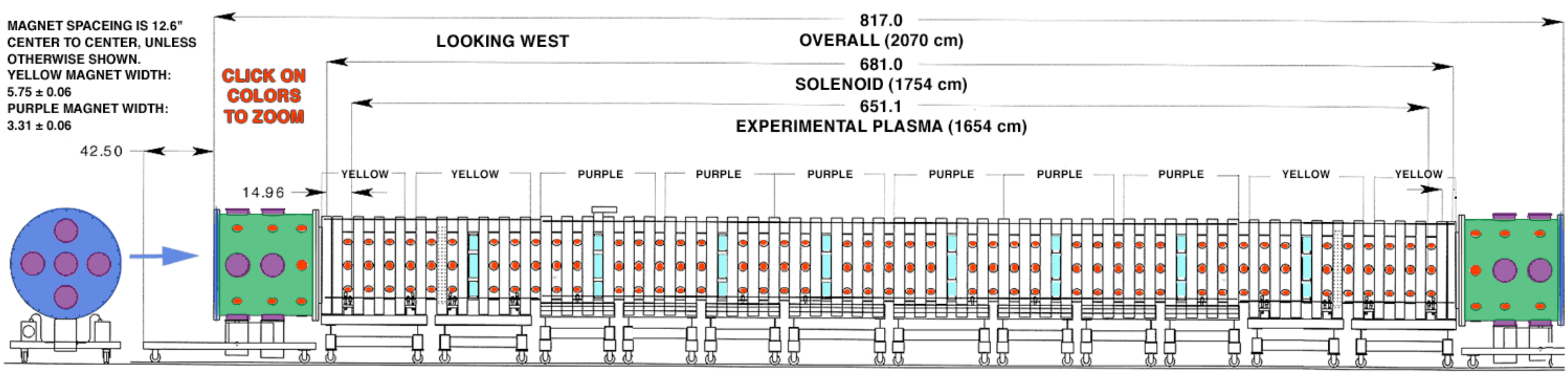
LAPD: Large Plasma Device

$T_e \sim 5$ eV

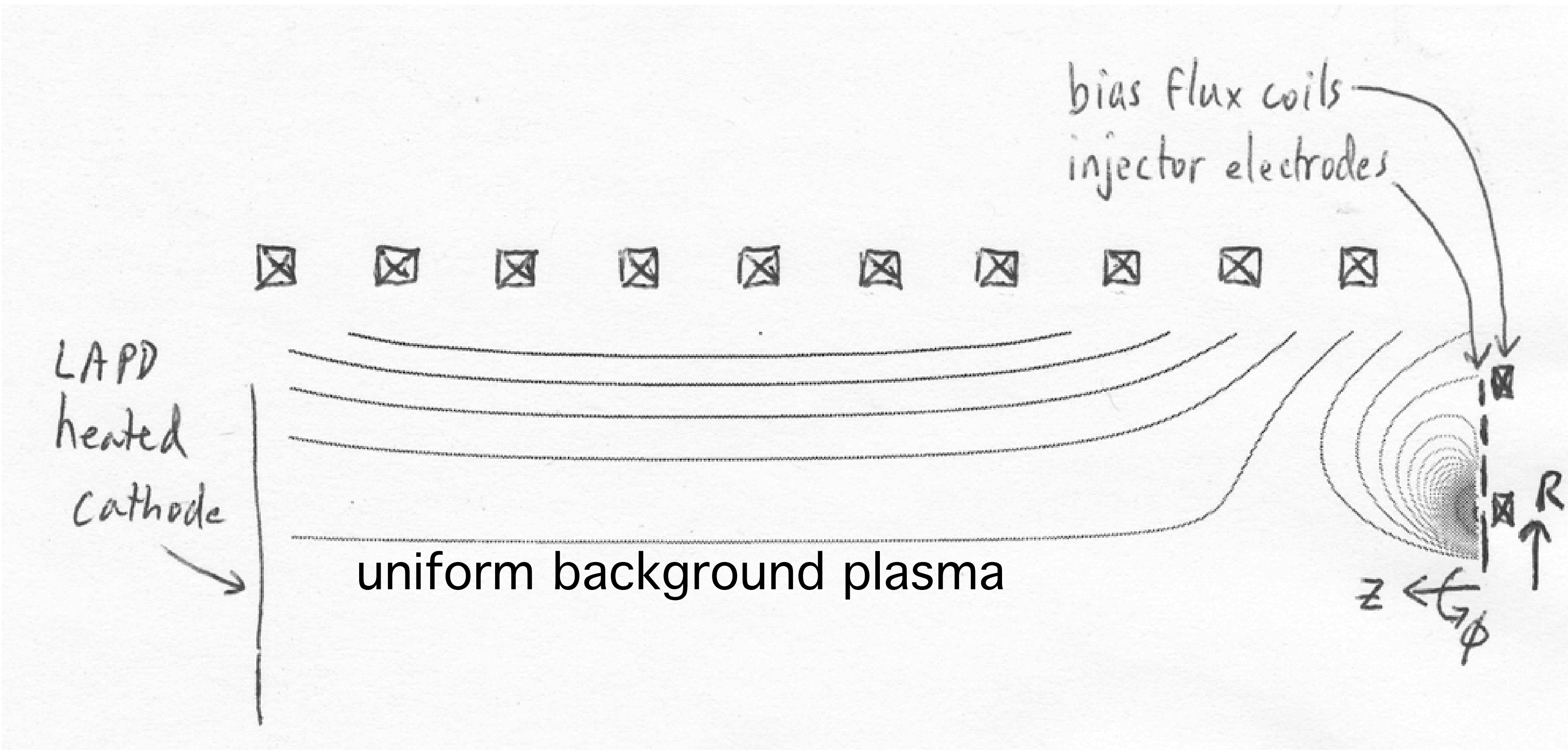
$n \sim 10^{12}$ cm^{-3}

$B \sim 1$ kG

5 ms duration
repeated at 1 Hz



We Will Install Concentric Ring Electrodes with Coil-Generated “Bias Flux” into LAPD

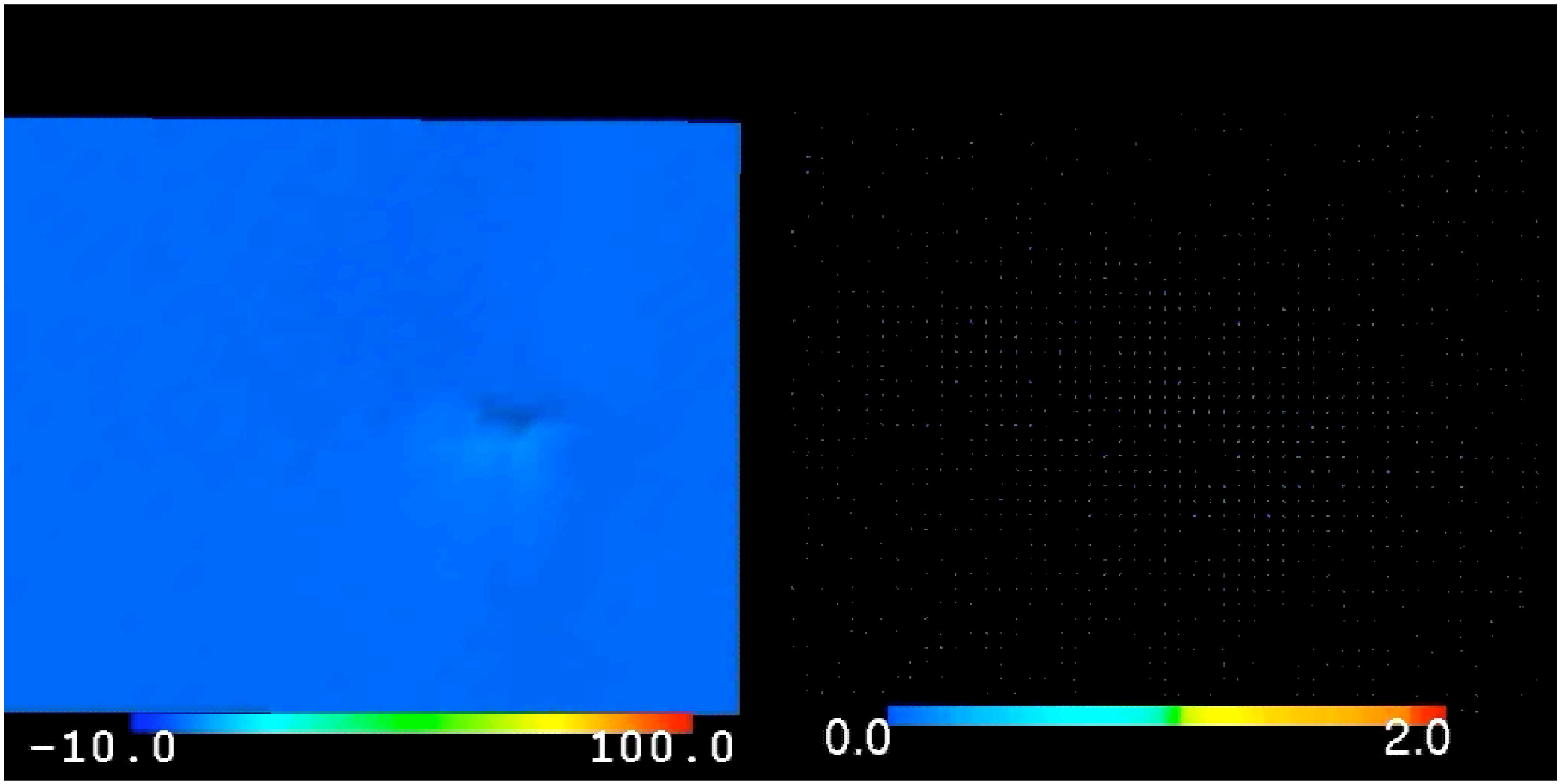


applied voltage between electrodes generated by switched capacitor banks

Research Plan

- Collimation dependence on helicity injection rate (scan $V_m \sim \rho^{1/2}\ V_{inj}/B_0{}^2$)
- Collimation dependence on jet stability (scan $V_s \sim V_{inj} q_0 / \eta B_0$)
- Study limits on jet magnetic energy and helicity content
- Magnetic energy dissipation and angular momentum transfer between jet and background

Example of Dataset We Will Obtain



B data (movie)

Courtesy of Prof. Walter Gekelman, UCLA

Summary

- Nonlinear plasma physics of jet formation need experimental tests
- Key dimensionless parameters can be reproduced in the lab
- Jet formation via helicity injection demonstrated on recent experiments
- New experiments have been designed for user facility LAPD at UCLA
- Experiments will address key open questions on the nonlinear plasma physics